Incorporating Objective Weights in the Risk Assessment of Wave Energy Converters

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ABSTRACT

It is necessary to minimize operational risks prior to a wave energy converter (WEC) being introduced to the market. Failure modes and their underlying causes can be identified by a failure analysis, typically with the aim of implementing remedial actions to address problems and lower the likelihood of future failures and costs. This study identifies failures and targets actions by conducting a failure mode, effects and criticality analysis (FMECA) on a generic WEC. It proposes a method of including objective weighting to the severity of components' failure consequences in the FMECA for a case study in the West of Ireland.

KEY WORDS: FMECA; WEC-subsystems; components; failure modes; risk mitigations; availability

INTRODUCTION

There are currently around 25 wave energy converter (WEC) demonstration projects underway across the world, with plans for implementing some of the devices in arrays (PRIMRE, 2023). The most promising technologies for commercialization, according to the International Renewable Energy Agency (IRENA, 2020), include point absorbers, oscillating water column and oscillating water surge converters. Nevertheless, the sector's shortcomings stem from a lack of design convergence. WEC design needs to be optimized so that WECs can become financially sustainable, requiring more reasonable capital and operating expenditures.

One approach towards reducing costs is to carry out a suitable risk assessment early in the project development process. Project risks do not have a single definition. Typical characteristics include the likelihood of an unplanned failure occurring and the possibility that it may negatively impact the project's safety and financial viability. If the risk assessment identifies the weak points in the WEC components, the effort to strengthen their reliability will be correctly targeted. Failure mode, effects, and criticality analysis (FMECA), an approach frequently employed in engineering applications, is a recommended and useful approach to risk assessment (Abu Dabous et al., 2021).

FMECA does however require large amounts of data, ideally gathered from the industrial partners' shared long-term operations in the sea, which is obviously not the case for WECs. None of the WEC technology has been able to operate in the water for an extended period of time, despite decades of testing and review. Moreover, because the technology is still in its infancy, industries are reluctant to share their knowledge, which makes solving problems more difficult. One approach to overcoming this difficulty is compiling data from similar industries, such as offshore wind or oil and gas, to build a database that will be used for the WEC FMECA. This study contributes to that approach.

As part of the European Union-funded project IMPACT (Innovative Methods for wave energy Pathways Acceleration through novel Criteria and Test rigs, (https://www.impact-h2020.eu/), such a database is constructed (Kamidelivand and Murphy, 2022). This publicly available FMECA data and other data from the literature is used in the current study to shed light on the crucial components of generic WEC systems. The study will broaden its approach to include objective criteria and estimate the criticality of failure mode consequences for a floating point absorber case study in the North East Atlantic region to the west of Ireland, taking into account both direct and indirect (production loss) effects.

The remainder of the paper is structured as follows: an explanation of the methodology is given after the introduction, and then the primary findings of the conventional FMECA are presented. Additionally, a suggested approach for integrating a random, unbiased mean time downtime at component levels using a Monte Carlo method for an Irish case study is included. Limitations that require further research and conclusions are presented at the end of the paper.

METHOD

In a semi-quantified FMECA method, a component's failure- is aligned as closely as possible with its failure modes and failure mechanisms. This facilitates identifying the underlying source of the risks and enables the choice of solutions that will prevent or mitigate the impact of a specific component failure. The most widely used standard in FMECA is MIL-STD-1629A which has been applied in many industries for general failure analysis. A prioritised list of failure modes, based on expected frequency and failure consequence severity (Snowberg and Weber, 2015), is included in the FMECA results. The simplified FMECA method employed in this study accounts for both the ranking of failure modes and failure effects. Fig.1 provides a basic summary of the study's methodology, which is discussed in more detail in this section.

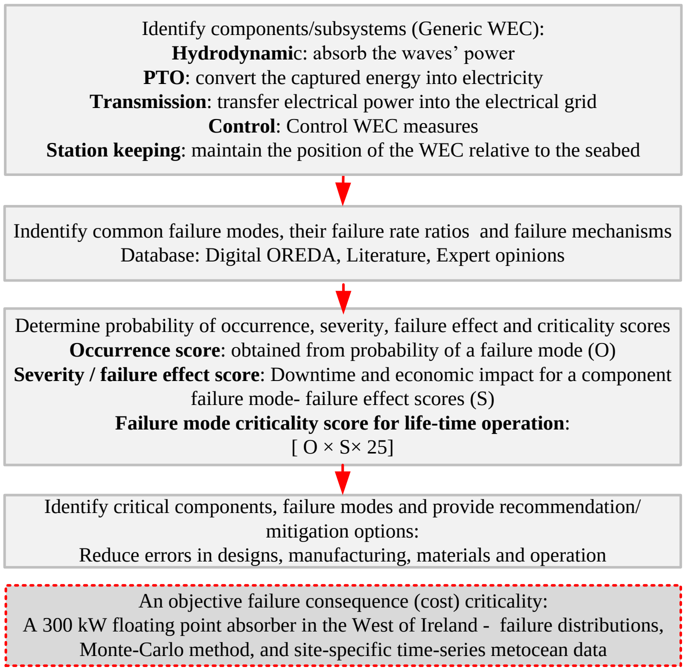

Figure 1 An overall description of the method.

WEC Subsystems

Despite a very large variety of WEC designs, a WEC can be decomposed into a number of generic subsystems : hydrodynamic subsystem, power-take-off (PTO) subsystem, transmission subsystem, instrumentation and control subsystem and reaction or station keeping subsystem (Hamedni, Ferreira, and Cocho, 2014).

The hydrodynamic subsystem's function is to absorb wave power. The WEC's absorber can be of several types, including a heaving buoy, a hinged flap, an oscillating water column, or a large surging body. A typical absorber consists of an oscillating body that interfaces with the PTO subsystem to extract power from the waves and the reaction subsystem to react to environmental stressors in an inertial frame.

Producing electricity from the energy converted by the hydrodynamic subsystem is the primary function of the PTO subsystem. The PTO is a key component of the WEC as it influences the efficiency of wave power conversion, as well as the mass, size, structural dynamics, and final levelized cost of energy. However, the lack of an industry-standard WEC mechanism or equipment has led to a somewhat wide range of PTO system designs in the ocean energy sector. PTO subsystems come in a variety of forms, such as linear generators, air turbines, hydraulic, and direct drive. An overview of the various PTOs and their operational principles can be found in (Tom, 2022). The PTO technologies covered by this study are hydraulic, rope and pulley, ball screw and rack and pinion.

The transmission subsystem's function is to deliver electricity in a format that is compatible with the electrical grid. Transformers, switchgear, connectors, and power cables make up most of its components. The instrumentation and control subsystem is the intelligent part of the WEC and regulates the WEC operation. It is made up of sensors (such as control, alarm, and monitoring sensors), processors, data collecting systems, communication and data transfer, and human-machine interface.

The function of the reaction and station keeping subsystem is to maintain the position of the WEC relative to the seabed. It provides a reaction point for PTO subsystem and provides a support for the hydrodynamic subsystem.

Data Source

As mentioned in the introduction, the main data source used in the study is the FMECA database for the IMPACT project (Kamidelivand & Murphy, 2022). In that database, one of the main data sources is the OREDA@CLOUD database where the reliability and maintenance data including the total number of failures per year for each relevant component, failure modes (description of the manner that failure occurs), failure mechanism (a primary reason behind the failure mode) and mean total repair time required to fix a component failure mode are collected. For failure data of those components that was not available in the OREDA database, the following literature sources are used: Structural Design of Wave Energy Devices (SDWED) report by DNV GL (Hamedni and Ferreira, 2014) for the component's failure mode of the non-hydraulic PTO subsystem and of the station keeping subsystem (generic WEC); and the Marine and Hydrokinetic Data Repository (MHKDR) (Rhinefrank, 2016) for the wave actuator body, failure ratios of the medium voltage frequency converter's failure modes, anchor and cable failure data. The estimated downtime (period of time that the WEC is not functioning due to the failure) and repair costs and their ranking is obtained from expert opinions which are explained in the following section.

FMECA Ranking Criteria

The FMECA uses ratings for the following criteria in Table 1:

- Occurrence rating (O) which rates the likelihood that the failure will occur is obtained from the range of annual failure rates (λ) for each component failure mode.
- Severity (failure effect) rating (S) is a combination of two rankings, both of which are based on educated assumptions and expert opinions. These rankings consist of:
  i) Downtime, which results in the economic production loss (indirect cost).

ii) Direct costs associated with the asset damage and repair, e.g. vessel hiring and fuel costs, costs for technicians and costs for replacement parts. Should there be a discrepancy in the severity ranking between the downtime and repair costs for a certain component failure mode, the higher-rated criteria will be given more weight in the severity rating. For instance, if the repair cost rating is one and the downtime rating is two, the severity rating would be two.

Both downtime and costs depend on the type of the WEC and deployment site characteristics (weather, water depth, distance of maintenance port facilities, logistics and vessel types). Small tugboats are usually required to tow the device to port for performing ex-situ (onshore) repairs on the structural components of the WEC. Tugboat costs and mobilisation times range, for example, from €1000 to €8000 per day (Lopez-Mendia et al., 2017) with a mobilisation period of less than a day or, in some cases, up to several days. Substructural component repairs, such as those involving mooring, cables, anchors, etc., are typically carried out in-situ (offshore) with the use of suitable vessels. One such vessel for a WEC would be a small, multipurpose workboat with a winch, enough deck space and dynamic positioning (Neary et al., 2014), for example, such a work boat could be rented for €20,000 per day and will mobilise in an average of 7 days.

Table 1 Occurrence adopted from (Rhinefrank, 2016) and Severity ratings.

Occurrence rating (O)	**Annual failure rate (λ)**	**MTBF (year)**
1 Very unlikey	Less 0.01	Above 100
2 Unlikely	0.01-0.03	100-30
3 Moderate	0.03-0.1	30-10
4 Likely	0.1-0.5	10-2
5 Very likely	Above 0.5	Less 2
Severity rating (S)	**Down-time in days (Affecting WEC operation)**	**Costs (k€)**
1 Insignificant	<3	1-5
2 Minor	3-8	5 - 15
3 Major	8-30	15 - 80
4 Critical	30-180	80 - 400
5 Catastrophic	>180	>400

The occurrence and severity rankings mentioned above are used to create a quantitative risk priority number as well as a qualitative risk assessment matrix in Table 2. The quantitative risk number for each failure mode is calculated by multiplying the Occurrence and Severity scores over a 25-year period, assuming a commercial WEC has a 25-year lifespan, comparable to offshore wind or tidal energy devices. Therefore, the lowest and highest life-time risk priority number, referred to as the "criticality number" in this study, will be 25 and 625, respectively. The greater the number, the more critical the failure mode. In addition, the study employs qualitative risk category colour coding —green for low risk, orange for medium risk, and red for high risk— along with high level recommendations as indicated in Table 2.

Table 2 Risk matrix for life-time 25 years.

Occurrence	Severity (×25)				
	1	2	3	4	5
5	125	250	375	500	625
4	100	200	300	400	500
3	75	150	225	300	375
2	50	100	150	200	250
1	25	50	75	100	125

≤100	Low- No urgent engineering action required
>100-250	Medium- Engineering actions to mitigate risk
>250	High- Engineering action is certainly required

Incorporating objective ranking

For a generic WEC in a generic location, the failure consequence severity criteria are derived from broad assumptions in the conventional FMECA, and the ranking scores are established by expert opinions. However, throughout the course of the WEC operation at sea, it is useful to understand the impact of the weather at the deployed site on the failure mode criticality results. For any project operating at sea, the weather window gap size (the minimum amount of time required to accomplish a repair operation under favourable weather conditions such as wind speed and wave height) and the weather window waiting time (the time spent waiting for such a gap to occur) may have a major influence on the costs associated with failure, both direct and indirect. The impact can be substantial if downtime or vessel use is prolonged, as repair costs are primarily determined by charted vessel costs rather than material costs for most of component failures, except for severe structural damage or complete loss of the device.

The Technology Collaboration Programme on Ocean Energy Systems (OES) places a strong focus on the need to move towards objective quantitative evaluation of ocean energy technology if practical (Hodges J et al., 2021). When analysing a case study for a certain WEC type at a specific place, the failure effect severity (downtime and costs in Table 1) can be determined objectively in a FMECA. It can use quantitative inputs that are similar to those used in an offshore operation and maintenance (O&M) and techno-economic model, such as (Gray et al., 2017). However, the method differs from an O&M model in that there is no interaction between component failures, and the model does not prioritise O&M tasks. In practice, several hundred Monte Carlo cycles are used to estimate the mean downtime and costs associated with a particular type of failure mode, with random failure times chosen from 25 years of metocean data. A uniform discrete distribution can be used for the Monte Carlo selections, with all possible times during the metocean data having an equal chance of occurring.

A floating point absorber WEC located in the West of Ireland is examined as a case study. The WEC's configuration and power curve is similar to the NREL Reference Model 3, and it is suitable for locations with water depth between 40-100m (Neary et al., 2014). It comprises of a spar buoy column that is coupled to a surface float and a submerged reaction heave plate. The relative motion of the two bodies pushes the hydraulic cylinder within the spar towards the hydraulic PTO, which converts wave energy into mechanical energy, which is then converted into electricity by an electric generator. The device is secured to the seabed using anchors and a three-line catenary mooring system. The deployment site's 25-year time series metocean data including the significant wave height, wave period and hourly wind speed off the West of Ireland are obtained from the database in the SELKIE project as explained by (O'Connell et al., 2024).

The conventional FMECA provides the failure modes and their failure rates for the case study components, whereas data from (Neary et al., 2014) and expert opinions are used to determine the costs of spare parts, mean time to repair and technician costs. Table 3 provides a summary of data used for the modified FMECA analysis.

Table 3 WEC case study-data summary.

Item	**Value**
WEC capacity	300 kW
Mean annual energy production	788 MWh
Average capacity factor	0.30
Electricity price	200 €/MWh
Tugboat (a pair) ; mobalization time	8,000 €/day; 96 hours
Multipurpose workboat (MPW); mobalization time	20,000 €/day; 168 hours
Maximum significant wave height & wind speed	1.20m & 15m/s for tugboats 1.75m & 20m/s for MPW
Site mean wave energy flux	40.2 kW/m
Site mean Hs; Tp; Wind	2.34m; 10.9s; 6.7m/s

The component failure mode criticality number will be calculated by Eq. 1:

$$crit_i = \frac{\lambda_i(dir_i+indir_i)}{\sum_{j=1}^{T}(dir_j+indir_j)} \qquad (1)$$

where $crit_i$ is the criticality number of the component failure mode i; λ_i is the probability of failure of i; dir_i is the direct failure mode consequence of i (costs of vessel, spare-part and technician); $indir_i$ is the indirect failure mode consequence of i (kWh downtime × unit price of electricity); and T is the total number of failure modes.

RESULTS AND DISCUSSION

This section discusses the FMECA results for each of the numerous components that make up a generic WEC and for the 57 components' failure modes that are displayed in Tables 4–9.

Structural Component of Hydrodynamic Subsystem

Table 4 presents the FMECA results of the hydrodynamic subsystem for the wave actuator body. The hydrodynamic structural component, which is typically made of steel and fibre-reinforced polymers, is one of the most expensive components of the WEC device (Hodges J et al., 2021). If the actuator body experiences a major structural breakdown that cannot be repaired, the project may fail. Even if the likelihood of failure is low, in circumstances where repair is feasible, the high cost of materials and the lengthy repair time place this component in the moderate to high-risk category in FMECA. The failure mode "hole/crack in float" accounts for 55% of the total criticality number in the table, owing to its high failure probability. With a criticality score of 250, the "severe structural material failure" is narrowly under the high-risk threshold, suggesting that this failure mode of the structural component should be carefully considered.

Performing routine maintenance, visual inspections, and the establishment of safety/exclusion zones are a few recommended actions to minimize failure during operation. Conducting hydrodynamic modelling, site characterization measurements, and design fatigue factors –see DNVGL-RP-C203 (2021)– is also advised in order to lower the level of uncertainty in loading estimates during the early stages of modelling and design. Additional thickness should also be taken into consideration in wear-prone areas.

Table 4 Hydrodynamic subsystem.

Component	Most Common failure mode	Annual failure rate [λ]	Lifetime criticality number [O×S×25]	Risk	Most common failure mechanisms
Hydrodynamic generic structural component	Sever structural material failure	0.010	250	🟧	Severe storm, lightening, corrosion, fatigue, collision
	Hole or crack in float body	0.032	300	🟥	
Total			**550**		

PTO Subsystem

The PTO subsystems that are studied in this paper include hydraulic PTO, Rack and pinion (RPi), Rope and pulley (RPu) and Ball screw (BS) that are provided in Table 5 and Table 6, respectively. The FMECA result of electric generator is presented as a separate component (Table 7), but it can be coupled with different other PTO mechanisms.

The distribution of the hydraulic PTO's overall criticality number at the component and failure mode levels is displayed in Table 5. The components that make up 84% of the PTO's overall estimated criticality number are, in order of importance, the heat exchanger (25%), hydraulic cylinders (21%), accumulators (19%) and pump (19%). The remaining numbers are: valves (7%), filters (6%) and manifold connector (3%).

The top five most critical failure modes, accounting for 72% of all failure mode criticality numbers, are: "leakage" in most parts and components, such as seals and subunits (e.g., lubrication); "pressure loss" in accumulators (with leakage as the dominant failure mechanism); actuators "mechanical failure"; motors "noise and vibration"; and actuators "bearing failure".

A number of mitigating strategies could be implemented during the manufacturing, operation and design phases:

- Employing a fluid with an acceptable viscosity index and good lubricating properties (Hamedni and Ferreia, 2014).
- By implementing condition-based-monitoring, such as using a pressure sensor or pressure transducer, it could be possible to detect oil or water leaks and prevent serious subsystem damage (Mountassir, 2018), (Mortazavizadeh et al., 2023). Also, the vibration should be regularly inspected, and if excessive vibration is discovered, action should be made to bring it down to a level below an acceptable maximum.
- Verifying the total loading during deployment and using site assessment data to determine loads that are prudent for the location (Rhinefrank, 2016).
- Considering risk reduction design measures such as redundant valves and filters.

Table 5 Hydraulic PTO subsystem.

Component	Most Common failure mode	Annual failure rate [λ]	Lifetime criticality number [O×S×25]	Risk	Most common failure mechanisms
Hydraulic linear actuator	External & internal leakage	0.20	300	🟥	Excessive side load, Seals failure, Contamination, fatigue, high pressure
	Bearing failure	0.08	225	🟧	
	Aeration & mechanical failure	0.10	300	🟥	
Valves general	Utility/ process leakage	0.14	100	🟩	Leakage, contamination, deformation, sticking, wear, unknown
	Fail to Regulate	0.10	100	🟩	
	Abnormal instrument reading	0.04	100	🟩	
Filter	Fail to	0.14	75	🟩	Instrument

	clean			🟩	failure, material failure, blocked
	External leakage	0.09	100	🟩	
	Abnormal instrument reading	0.06	75	🟩	
Manifold connector	External-process leakage	0.02	100	🟩	Looseness, wear
Pump/Motor	Process /utility medium leakage	0.27	300	🟥	
	Noise & vibration	0.13	300	🟥	
	Parameter deviation	0.08	150	🟧	
Accumulator	Pressure loss	0.17	200	🟧	Leakage, piston jammed, contamination, wear and corrosion
	External leakage	0.08	150	🟧	
	Gas & oil mixture	0.05	150	🟧	
	Breakdown	0.03	225	🟧	
Heat exchanger (generic)	Utility /process medium leakage	0.10	300	🟥	Blockage/ plugged, corrosion, leakage, material failure, mechanical failure, unknown
	Abnormal instrument reading	0.07	150	🟧	
	Structural deficiency	0.01	150	🟧	
	In-sufficient heat transfer	0.05	225	🟧	
	Other	0.02	150	🟧	
Total			**3900**		

Non-hydraulic PTOs Subsystems

The FMECA outputs of non-hydraulic PTOs are presented in Table 6. Because of the small number of components involved, low occurrence rates, low prices, or both, the results demonstrate that the risks associated with the failure modes in these PTOs are low to moderate.

The intermediate risk failure modes (mainly fracture and surface damage) in the various parts of these three PTOs that require attention are highlighted below:

- **Rope and Pulley**: Moderate risks of fracture and surface damage failure modes affect the belt component; these two types of failures account for 74% of the total criticality number of the belt and 28% of the overall criticality number of PTO. These failure modes represent 40% of the total PTO criticality number for both the rotary bearing and pulley components, despite being considered low risk due to their low failure probability.
- **Ball screw**: All failure modes of the ball screw PTO are low risk, with the exception of the moderate risk of the fracture failure mode of the screw nut and gear.
- **Rack and Pinion**: In the rail and assembly component, and the gear component, fracture failure modes are moderately risky accounting for 26% of overall criticality for this PTO.

Most of failure mechanisms linked to the component failure modes in Table 1, including fatigue, wear, corrosion, vibration, and so forth, are attributed to mistakes in design or manufacturing. For example, cyclic pressures applied to the contact surface that surpass the material's fatigue resistance typically result in surface degradation (ROMEO-D2.1, 2020). However, these failure modes may be mitigated by ensuring there is adequate lubrication, potentially by introducing an auxiliary lubrication system or doing routine maintenance that involves both lubrication and cleaning.

Table 6 Rope and pulley (RPu) PTO, Ball screw (BS) PTO, Rack and Pinion (RPi) PTO.

Com-ponent	Most Common failure mode	Annual failure rate [λ]	Lifetime criticality number [O×S×25]	Risk	Most common failure mechanisms
Belt [1]	Surface damage	0.10	200	🟧	Fatigue, wear, foreign materials, misalignment, corrosion, vibration, lubrication failed
	Fracture	0.05	225	🟧	
	Deformation	0.02	150	🟩	
Pulley [1]	Surface damage	0.03	150	🟩	
	Fracture	0.01	150	🟩	
	Deformation	0.002	75	🟩	
Rotary Bearing unit [1, 3]	Surface damage	0.04	150	🟩	
	Fracture	0.01	150	🟩	
	Deformation	0.005	75	🟩	
Shaft [1, 2, 3]	Surface damage	0.006	50	🟩	
	Fracture	0.004	75	🟩	
	Deformation	0.002	75	🟩	
Screw nut [2]	Surface damage	0.03	150	🟩	
	Fracture	0.07	225	🟧	
	Deformation	0.004	75	🟩	
Screw and rail assembly [2]	Surface damage	0.02	100	🟩	
	Fracture	0.005	75	🟩	
	Deformation	0.002	75	🟩	
Gear [2,3]	Surface damage	0.02	100	🟩	
	Fracture	0.03	225	🟧	
	Deformation	0.002	75	🟩	
Linear bearing unit [3]	Surface damage	0.02	100	🟩	
	Fracture	0.01	150	🟩	
	Deformation	0.003	75	🟩	
Rail assembly [3]	Surface damage	0.03	150	🟩	
	Fracture	0.07	225	🟧	
	Deformation	0.004	75	🟩	
Total RPu			**1525**		
Total BS			**1300**		
Total RPi			**1750**		

[1] RPu PTO; [2] BS PTO; [3] RPi PTO

Electric Generator

Table 7 presents the results of the FMECA for a generic electric generator. Low output voltage (high-risk), leakage (e.g., insulation loss), overheating and abnormal instrument reading appear to be the top four important failure modes to be mindful of, with 73% of the component criticality number. These and other failure mechanisms listed in Table 7 implies that the main root causes are errors linked to design (e.g., underestimating operational temperature) and manufacturing (e.g., insulation deterioration) (Scheu et al., 2019). Nonetheless, it seems that providing a monitoring system that evaluates the generator's internal temperature, vibration, and moisture content (Scheu et al., 2019), as well as establishing the proper intervals for preventative maintenance, are essential mitigating actions for the electric generator component with a relatively high criticality number.

Table 7 Generator (generic).

Component	Most Common failure mode	Annual failure rate (λ)	Lifetime criticality number [O×S×25]	Risk	Most common failure mechanisms
Generator (generic)	Abnormal instrument reading	0.10	200	🟧	Electrical failure (general), faulty signal, leakage, mechanical failure, control failure, vibration, unknown
	Utility medium leakage	0.08	225	🟧	
	Overheating	0.06	225	🟧	
	Low/faulty output voltage	0.11	300	🟥	
	Fail to synchronize	0.07	150	🟩	
	Parameter deviation	0.01	100	🟩	
	Other	0.02	100	🟩	
Total			**1300**		

Transmission and Control Subsystem

The result of FMECA analysis of ‘power transmission and control’ subsystems are combined in Table 8. For this subsystem, the generic components include ‘frequency converter’, ‘switchgear’, ‘valve positioning sensors’, ‘programmable logic controller (PLC)’ and ‘cables’. Of the overall criticality number for this subsystem, 32% allocated to frequency converter and switchgear components, 34% to control components (PLC and sensors) and 34% to cable.

Most failure modes in these components are ranked as low risks because of their low probability of occurring. However, the overheating failure mode in the frequency converter and mechanical and electrical failure modes in cables are medium to high risk, making up roughly 16% and 34% of the subsystem’s total criticality number, respectively. Cable failure modes, particularly the electrical failure mode, are classified as high-risk failure modes due to the substantial costs and downtime associated with a failure if it occurs. Failure may cause a loss of grid connection.

The failure mechanisms listed in Table 8 imply multiple root causes of manufacturing, material and design errors as well as incorrect installation and operation, which should be taken into consideration. For example, corrosion-induced failure mechanisms may have their roots in FLS (fatigue limited state) design constraints. Improper installation could result from inadequate internal quality control and component testing conducted by the manufacturer (Rhinefrank, 2016) or installation contractors (e.g. for cables). Cables must undergo post-installation testing to ensure that the installation did not impair their technical parameters, as well as factory tests (e.g., voltage test, jacket tightness, micro-damage, etc.) before being passed onto the vessel (Gulski et al., 2021).

Table 8 Power transmission and control subsystem- Generic WEC.

Component	Most Common failure mode	Annual failure rate [λ]	Lifetime criticality number [O×S×25]	Risk	Most common failure mechanisms
Frequency converter (Medium Voltage)	Fail to function/ start on demand	0.003	50	🟩	Blockage, general electrical & mechanical induced factors, leakage, open circuit, corrosion, vibration, software failure, unknown
	Spurious stop	0.003	50	🟩	
	Parameter deviation	0.003	50	🟩	
	Over-heating	0.05	300	🟥	
Switchgear	Fail to function on demand	0.004	75	🟩	
	Spurious stop	0.003	75	🟩	
Valve Positioning sensor	Control/ signal failure	0.02	100	🟩	
	Erratic output	0.004	75	🟩	
PLC	Fail to function on demand	0.01	150	🟩	
	Spurious stop	0.03	150	🟩	
	Low output	0.02	150	🟩	
Cable	Mechanical failure	0.01	250	🟧	Improper installation, damage to tension member & insultation, motion induced failure, corrosion, wear
	Electrical failure	0.03	375	🟥	
Total			**1850**		

Reaction and Station keeping Subsystem

Table 9 demonstrates the generic components of the reaction and station keeping subsystem, which include ‘fibre rope’, ‘chain’, ‘joints and connections’, ‘floating support structure’ and ‘fixed support structure’. The findings indicate that the mooring system's joint and connection components have high-risk failure modes due to their high probability of occurrence and severity (long downtime or expensive repairs). The failure mode of the rope or chain termination point, the material failure mode of the anchor, and the failure mode of the loss of anchoring capacity are the three failure modes with a moderate risk rating that are bordering on high risk. As the table indicates, common failure mechanisms (e.g., fatigue, ultimate limit state, corrosion, etc.) are mostly associated with design criteria that must be taken into account.

Some recommended actions from (Rhinefrank, 2016) include making sure that a corrosion allowance is defined as per DNV-OS-E301 (e.g. for chain and bridle shackles, including wear and tear) while taking annual inspection into account; proving that anchor capacity at the deployed site satisfies design requirements (full scale testing following installation); offering a third-party certification of the properties of used mooring components; and using a load calculation method to account for loading errors resulting from hydrodynamic models and site characterization observations.

In general, risk assessments should place greater emphasis on the WEC's reaction and station keeping subsystem because it interacts with the PTO and hydrodynamic subsystems (Hamedni and Ferreia, 2014). Even though there is a small likelihood of the floating and fixed support structures failing, it is still necessary to increase their reliability because their failure would have significant financial consequences.

Table 9 Reaction and station keeping subsystem.

Component	Most Common failure mode	Annual failure rate [λ]	Lifetime criticality number [O×S×2]	Risk	Most Common failure mechanisms
Fibre/Rope /Chain	Rope material failure	0.008	125	🟩	Fatigue, Creep, Wear, Corrosion, ULS
	Termination point failure	0.012	250	🟧	

Joints & Connection	Material failure of body	0.086	300	🟥	Fatigue, Corrosion, Marine growth
Anchor	Material failure	0.01	250	🟧	Extreme load, Fatigue/cycling loading, sediment loss
	Loss in anchoring capacity	0.01	250	🟧	
Floating support structure	Instability	0.001	125	🟩	Fatigue, Corrosion, ULS*
	Change in buoyancy	0.001	125	🟩	
	Change in hydrodynamic properties	0.001	125	🟩	
	Loss of support	0.003	125	🟩	
Fixed support structure	Loss of support	0.001	125	🟩	Fatigue, Corrosion, Wear, ALS*
Total			**1800**		

* Ultimate Limit State (ULS): A state of approaching collapse, beyond which a structure can no longer fulfil its original purpose that ensures either serviceability or safety. Accidental Limit State (ALS): An exceeding of ALS condition results in a loss of structural integrity caused by an accidental load.

FMECA Case Study

Using the method in the previous section and Eq. 1, the case-study-FMECA's findings are calculated and the average results of 500 simulations are shown in Fig. 2[1]. In the figure, the percentage criticality scores of each of the 49 potential component failure modes, together with the relative contributions of each subsystem to the overall system criticality, are shown. For instance, the hydraulic PTO and electric generator accounts for roughly 72% of the system's total criticality; similarly, joints and connections in the mooring system and cable electrical failure in the station keeping system are critical, and so forth.

For each of the 17 components included in the case study, the direct and indirect effects are displayed proportionally in Fig. 3. Since the indirect effect results from downtime, it is possible to determine the impact on availability for every failure. As shown in Fig. 3, PTO component failures are the largest contributor to reduced availability. For this case study, availability is determined to be 86%. The measurement of this indirect effect and decreased availability has implications for the levelized cost of energy (LCOE) from the design optimisation stage to the commercial-scale array demonstration (Hodges J et al., 2021); and availability is of the techno-economic metrics (Rodrigues et al., 2023). The impact will be more pronounced if the device capacity factor or its rated power increases.

The model can be upgraded to become an O&M tool to investigate and determine, for example, optimal planned maintenance intervals (Kamidelivand et al., 2023), if one of the FMECA recommendations for critical component failure modes is a suitable maintenance strategy. This offers an idea of how the current study's scope might be expanded in the future. Conducting sensitivity analyses for the inputs (failure rates, mean time to repair, vessel types, port distances, spare parts, etc.) is another avenue for further research. Thus, scenarios with low, medium and high criticality numbers, for instance, may be more helpful in assisting with decision-making and prioritising mitigation measures. In the next study, it will also be important to analyze more case studies pertaining to the different WEC types in various locations.

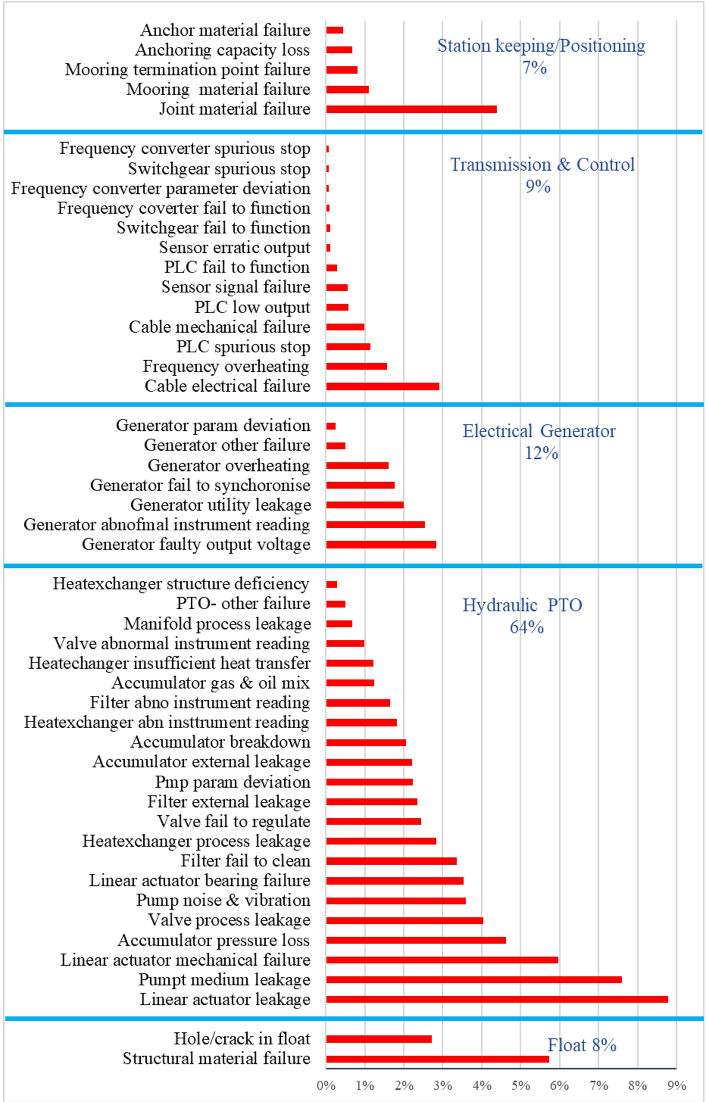

Fig. 2. Distribution of criticality shares among all subsystems - a 300kW point absorber case study.

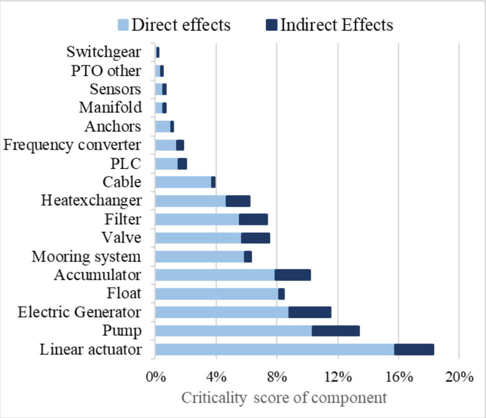

Fig. 3. Distribution of the components' direct and indirect criticalities.

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[1] An explanation for the 500 simulations that were chosen for this case study can be found in the Appendix.

The FMECA described in this study is limited to assessing risks in terms of costs and financial losses associated with various failure modes. Although this element is highly significant for the WEC because its development is hampered mainly due to its high costs, other risk aspects such as environmental and safety risks related with installation, operation, and decommissioning are worth studying. These aspects should also be included in future study when data is available.

CONCLUSIONS

While there is a dearth of reliability data for WEC components, by using data from other offshore industries and expert opinions, a conventional FMECA can offer insights into component failure modes and criticality prioritisation. The criticality of 57 potential component failure modes spread throughout WEC subsystems was ranked in this study. It discussed the critical failure modes of the components in the hydrodynamic, PTO, electric generator, transmission, control and reaction-positioning subsystems that need to be monitored closely. High-level mitigations are recommended based on the potential root failures, which include errors in design, materials, manufacturing and operations. It is advantageous to reduce the subjective elements of a traditional FMECA for a specific WEC at a location and to allow for a comparison of the criticality of components with respect to availability (due to downtime), production loss, and direct consequences. This research employed a model to objectively evaluate these failure effects impacts for each of the 46 component failure modes involved in an assumed floating point absorber WEC with a capacity of 300 kW, situated in the North East Atlantic region.

Although, the study offered both qualitative and quantitative risk estimates for a reasonable range of WEC failure modes, it is evident that more data from WEC operations on the water is needed to conduct accurate risk assessments. The reliability of the WEC's components should be investigated further through extensive research and testing (on rigs and at sea). This will facilitate future technical and financial analyses that will ascertain that WECs constitute a cost-effective and reliable means of producing power.

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APPENDIXES

A large number Monte Carlo simulations can help to improve the accuracy of the findings. The case study influences the number of simulations chosen, which depends on component failure rates across WEC types, repair vessel types and costs, and location accessibility. For this case study, 500 simulations selected based on a pre-analysis. Figure 4 depicts the size of the 95% confidence interval (CI) for the failure consequence cost impact for each of the 49 component failure modes (FM), expressed as a percentage of the mean failure consequence cost per component.

The graph shows that as the number of Monte Carlo simulations (N) increases, the size of the confidence interval decreases. For example, for N = 10, the CI for component FM35 (transformer overheating) is +/-30.5%, which is quite large, whereas for N = 500 for the same component, the CI is less than +/-3.3%.

After 500 simulations, there is a consistent decreasing pattern of CI size. For 500 simulations, the maximum CI for all 49 component failure modes is less than +/-4%, which is acceptable. Furthermore, increasing N does not significantly reduce the CI size while increasing computing time. Thus, N = 500 is appropriate for this study.

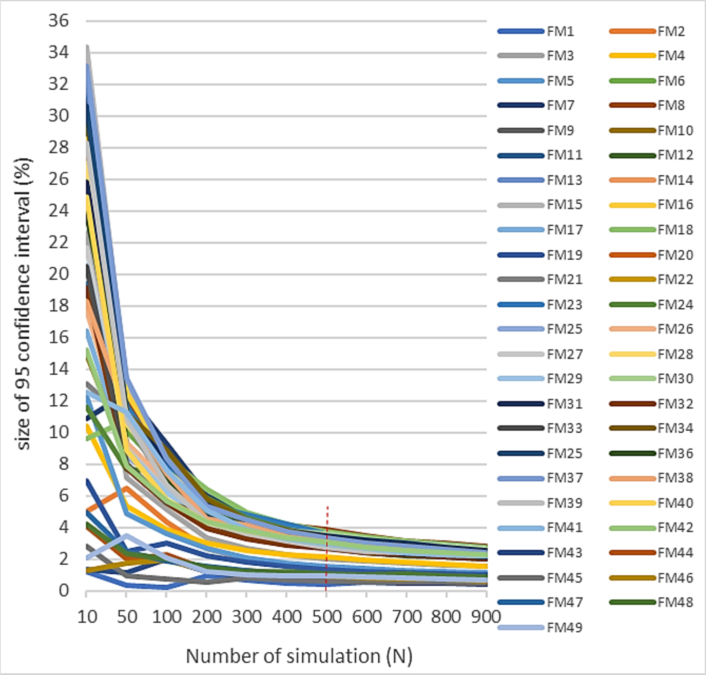

Fig. 4. Size of confidence interval as a percentage of each measure for component failure modes.